

Effect of Initial Temperature on the Flashback of Laminar  
and Turbulent Burner Flames

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ABSTRACT

The effect of elevated initial temperature on the critical boundary velocity gradient for the flashback of laminar and turbulent flames has been measured for flames of hydrogen and ethylene with air and propane and ethylene with mixtures of 50 percent oxygen and 50 percent nitrogen by volume. For each fuel-oxidant system measurements have been made at a single equivalence ratio close to that giving the maximum gradient. For each system the dependence of the critical boundary velocity gradient on initial temperature is the same for laminar and turbulent conditions. This is consistent with the concept that a turbulent burner flame near flashback is stabilized in a near-laminar portion of the boundary layer. The extent of variation of the critical gradient with initial temperature differs markedly among the several systems studied.

Not for Publication  
Presented Before the Division of Gas and Fuel Chemistry  
American Chemical Society  
Urbana, Illinois, Meeting, May 15 and 16, 1958

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SUMMARY

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INTRODUCTION

Several studies have recently been reported of the effect of elevated temperature on the flashback of burner flames. Bollinger and Edse<sup>1</sup> and Miller and Setzer<sup>2</sup> studied flashback under the condition that only the burner lip was heated, the gas stream being approximately at room temperature. Grumer and Harris<sup>3</sup> and Dugger<sup>4</sup>, on the other hand, maintained nearly the same temperature for both the gas stream and burner lip. By this latter technique flashback data could be treated by a simple critical boundary velocity gradient which did not involve a transverse temperature gradient.

The purpose of the present study is to extend the measurements of Grumer and Harris and of Dugger on laminar hydrocarbon-air flames to chemically related systems of higher reactivity and, systematically, to the turbulent regime. Measurements are reported over a temperature range from about 300° to 660° K and a pressure range from 0.1 to 1.0 atmospheres corresponding to Reynolds numbers from 300 to 5000. Four systems have been studied: hydrogen-air, ethylene-air and propane and ethylene with mixtures of 50 percent oxygen and 50 percent nitrogen by volume. Measurements at elevated temperatures have been made with a single burner at a single equivalence ratio for each system. All data reported at room temperature, however, were obtained with several burners of different diameters.

1. Bollinger, L. and Edse, R.: Ind. and Eng. Chem. Vol. 48, no. 4 (1956), pp. 802-807.

2. Miller, E. and Setzer, H. J.: Sixth Symposium (International) On Combustion. P. 164. Reinhold Publishing Co., New York, (1957).

3. Grumer, J. and Harris, M.: Ind. and Eng. Chem., Vol. 46, no. 11 (1954), pp. 2424-2431.

4. Dugger, G.: Ind. and Eng. Chem., Vol. 47, pp. 109-113, (1955).

Materials. - Tank hydrogen (99 percent  $H_2$ ) and propane and ethylene of C.P. grade were used as fuels. Tank compressed air and a prepared mixture, 50 percent oxygen and 50 percent nitrogen by volume were used as oxidants. All materials were used without further purification.

Apparatus. - The low-pressure combustion chamber and the gas metering system, based on critical flow orifices, have been described in detail elsewhere<sup>5</sup>. The burner was a straight brass tube which had a length of about 125 cm, an inside diameter of 1.016 cm and a wall thickness of about 0.16 cm. It was fitted to the low-pressure combustion chamber as shown in Fig. 1. The part of the burner outside the combustion chamber was wrapped with asbestos-covered nichrome heating wire and thermally insulated. The part of the burner inside the chamber was heated by a separate wrapping of nichrome. A chromel-alumel thermocouple was held under its own tension in a well about 0.08 cm deep drilled into the tube wall about 0.15 cm below the lip. The reading given by the thermocouple was taken to be the temperature of the burner lip. The gas temperature, determined only in the absence of a flame, was taken to be the reading given by a bare wire thermocouple held at the center of the tube mouth, as shown in Fig. 1.

Procedure. - The absolute gas temperature was measured before and after each short series of flashback measurements; it was constant to  $\pm 2$  percent. Measurement was made with the small inner heater energized to partially simulate the effect of heating of the burner lip by the flame. The difference between gas temperatures measured with and without energizing of the inner heating coil was never more than  $10^\circ K$ . The gas temperature was found to vary somewhat with flow rate for a given energy input, decreasing slightly as flow changed from laminar to turbulent. This decrease was overcome by adding a predetermined amount of energy in the course of a series of flashback measurements.

In measuring flashback, a stable flame was established at some pressure. The energy input to the small inner heater was then adjusted so that the lip temperature approximated the gas temperature to within  $5^\circ$  to  $10^\circ K$ . The pressure was then slowly increased, at constant mass flow, until the flame flashed back<sup>6</sup>. For the hotter flame systems, heating of the burner lip by the flame was so great that equalization of gas and lip temperatures was possible only for very high gas temperatures. To obtain results for hotter flames at lower initial temperatures (specifically, propane-oxygen-nitrogen at  $394^\circ K$ ) the burner was joined to the combustion chamber with a brass flange so that much of the heat fed to the burner lip by the flame was removed by conduction. In this case, the difference between gas and lip temperatures was  $30^\circ K$ .

Reduction of data. - A value of  $\bar{U}_f$ , the average stream velocity at flashback<sup>6</sup>, was computed from the chamber pressure,  $P$ , burner diameter,  $D$ , temperature of unburned gas,  $T$  and nominal volume flow rate at 1 atmosphere pressure,  $V^0$ , by

$$\bar{U}_f = \frac{P^0}{P} \frac{T}{T^0} \frac{4V^0}{\pi D^2} \quad (1)$$

The superscript zero denotes conditions near 1 atmosphere and room temperature to which calibrations of critical flow orifices, used in metering the gases, were referred.

5. Fine, B.: NACA TN 3833 (1956).

6. The subscript "f" refers to flashback conditions.

For laminar flames, critical boundary velocity gradients for flashback were computed by the expression used for fully developed laminar flow<sup>7</sup>

$$g_f = \frac{8\bar{U}_f}{D} \quad (2)$$

For turbulent flames the expression (ref. 7, p. 297)

$$g_f(t) = 0.023 \frac{\bar{U}_f}{D} Re_f^{0.8} \quad (3)$$

was used where  $Re_f$  is Reynolds number at flashback defined as

$$Re_f = \frac{\bar{U}_f D \rho}{\mu} \quad (4)$$

Here,  $\rho$  is the mixture density and  $\mu$  its viscosity. In the region of laminar-turbulent transition, critical flashback gradients were computed as for laminar flames. Justification for this procedure has been offered in a previous publication.<sup>9</sup>

## RESULTS AND DISCUSSION

Description of results. - Experimental data for the four flame systems studied are shown in the right-hand parts of Figs 2 to 5. Results are plotted as  $\log g_f$  against  $\log P$  for values of  $T$  from  $394^\circ$  up to  $660^\circ$  K. Also shown are results obtained at room temperature; except for ethylene-air, these results were obtained in water-cooled burners. Results for hydrogen-air and propane-oxygen-nitrogen flames at room temperature had been reported previously<sup>5,9,10</sup>; and are shown as dashed lines in Figs. 2 and 3. Results for ethylene-air, nominally at room temperature, were cross-plotted from the data of Garside, Forsyth and Townend<sup>11</sup> who used an uncooled burner 1 cm in. diameter. For each flame, data are presented at a single equivalence ratio which was close to the equivalence ratio giving the maximum value of  $g_f$ . For hydrogen-air, an equivalence ratio of 1.50 was chosen; for ethylene-air, 1.17; and for propane-oxygen-nitrogen and ethylene-oxygen-nitrogen, 1.00. Results for turbulent flames are shown for two systems, hydrogen-air and propane-oxygen-nitrogen.

Flashback curves at constant initial temperature show three main regions for the range of conditions shown in Figs. 2 to 5: a laminar region for Reynolds numbers less than about 1500, a transition region between 1500 and about 2500, and a turbulent region for Reynolds numbers greater than 2500. In the laminar and turbulent regions critical boundary velocity gradients for flashback are dependent on both pressure and initial temperature. The exponential pressure dependence of  $g_f$ , however, is nearly independent of initial temperature. Some curvature is found in the plots of  $\log g_f$  against  $\log P$  at low Reynolds number, which is attributed to partial quenching of the flame by the wall. This has been

7. Lewis, and von Elbe: Combustion Flames and Explosions. p. 279, Academic Press, New York, (1951).

8. The symbol (t) denotes turbulent conditions.

9. Fine, B.: NACA TN 3977, (1957).

10. Fine, B.: NACA TN 4031, (1957).

11. Garside, J. E., Forsyth, J. S., and Townend, D. T. E.: Jour. Inst. Fuel, Vol. 18, no. 103. (1945), pp. 175-185.

discussed in more detail in a previous publication<sup>9</sup>. A small change in slope is sometimes found for turbulent flames at high initial temperatures. This may be because the amount of additional energy added at high flows was not sufficient to maintain the temperature at its nominal value.

At the beginning of the transition region (Figs. 2 and 3), the flashback pressure at constant initial temperature goes through a slight maximum, levels off and then remains constant with increasing Reynolds number until flames are fully turbulent. The flashback pressure at the maximum increases slightly with increasing initial temperature so that Reynolds number of the maximum remains about constant.

Temperature dependence of laminar and turbulent flashback. - The variation of  $g_f$  is assumed to be described by a relation of the form  $g_f \propto P^a T^b$ , so that  $a$  and  $b$ , taken to be constant, denote the "dependence" of  $g_f$  on pressure and initial temperature. Because the dependence of  $g_f$  on initial temperature is nearly independent of its dependence on pressure, the critical flashback gradient may be cross-plotted against  $T$  at constant  $P$ . Logarithmic plots of this kind are shown on the left-hand side of Figs. 2 to 5 for both laminar and turbulent flames. (The points shown in these cross-plots are not experimental, but were taken from the smooth curves which describe  $g_f$  as a function of  $P$ .) The plots show no curvature and only slight scatter. Values for the exponents which describe the temperature dependences found are shown in table I.

Two general features of the cross-plots should be noted. First, if one extends the lines describing  $g_f$  as a function of temperature to lower values of  $T$  it is found that values of  $g_f$  obtained in water-cooled burners correspond to initial temperatures of about 300° K. Thus, data obtained by varying pressure at elevated initial temperatures are consistent with those obtained by varying pressure at room temperature. The data obtained for ethylene-air in an uncooled burner correspond to a slightly higher initial temperature, about 340° K. This is consistent with the general observation that heating of the burner lip increases  $g_f$  (ref. 1). Second, the temperature dependence of the critical flashback gradient is the same, within experimental error, for both laminar and turbulent flames. Thus,  $g_f$  is proportional to  $g_f(t)$  over a range of  $T$ . By judiciously extrapolating plots of  $\log g_f$  versus  $\log P$  one may estimate the coefficient of proportionality; a value of about 2.5 to 3 is found. Increases of this magnitude in the critical flashback gradient with turbulence have been observed by others, notably Wohl<sup>12</sup>, Bollinger and Edsel<sup>1</sup>, and Boyer and Friebertshauser<sup>13</sup>.

Dependence of  $g_f$  on initial temperature and flame temperature. - The first column of table I shows the dependence of  $g_f$  on initial temperature for the four systems studied in this investigation. The numbers shown are averages of laminar and turbulent values. In addition there is shown the dependence on initial temperature obtained from the data of Grumer and Harris<sup>5</sup> for methane-air. It is seen that  $(\partial \ln g_f / \partial \ln T)_P$  varies by more than a factor of two among the flames considered, generally decreasing with increasing  $g_f$  for hydrocarbon flames. For the most reactive flames considered, those of propane-oxygen-nitrogen and ethylene-

12. Wohl, K.: Fourth Symposium (International) on Combustion. The Williams and Wilkins Co., (Baltimore), pp. 68-89 (1953).

13. Boyer, M. H., and Friebertshauser, P. E.: Combustion and Flame. Vol. 1, no. 3, 1957, p. 264.

oxygen-nitrogen,  $g_f$  is nearly proportional to the first power of  $T$ , so that the mass flow rate at flashback is nearly independent of initial temperature.

Since  $g_f$  may be considered to be a measure of the mean reaction time, an expression of the form  $\partial \ln(g_f A) / \partial (1/T_b)$ , where  $A$  is the fuel concentration in moles per unit volume, should give an Arrhenius-type dependence of the mean flame reaction rate on flame temperature,  $T_b$ . If the initial temperature,  $T$ , is the only experimental variable, the dependence may be expressed as

$$\frac{\partial \ln(g_f A)}{\partial (1/T_b)} = - T_b \left[ \left( \frac{\partial \ln g_f}{\partial \ln T} \right)_P - 1 \right] \left( \frac{\partial \ln T_b}{\partial \ln T} \right)_P^{-1} \quad (5)$$

For methane-air flames,  $(\partial \ln T_b / \partial \ln T)_P$ , based on calculated flame temperatures is about 0.12<sup>4</sup> at an equivalence ratio of 1.22. For ethylene-air, a value of about 0.088 is obtained<sup>4</sup> at an equivalence ratio of 1.17. Evaluation of Eq. (5) in terms of  $(\partial \ln g_f / \partial \ln T)_P$  from table I gives "activation energies" of about 45 kcal/mole for methane-air and 31 for ethylene-air. The value for hydrogen-air, based on  $(\partial \ln T_b / \partial \ln T)_P = 0.12$  at  $\phi = 1.50$ <sup>14</sup> is about 19. For hydrocarbons burning in 50 percent oxygen, both  $(\partial \ln T_b / \partial \ln T)_P$ <sup>15</sup> and  $[(\partial \ln g_f / \partial \ln T)_P - 1]$  are sufficiently close to zero that experimental uncertainty makes evaluation of Eq. (5) impossible.

Relation of temperature dependence of laminar flashback to other properties of burner flames. - For many flame systems the relation

$$g_f = \frac{C_1 U_b}{D_q} \quad (6)$$

has been observed<sup>5,16</sup> where  $U_b$  is the burning velocity,  $D_q$  the quenching distance and  $C_1$  a coefficient which increases slightly with increasing  $g_f$ . The form of Eq. (6) follows from consideration of  $g_f$  as a measure of the mean flame reaction time. A second relation which has been observed among burner flames is<sup>17</sup>

$$\frac{U_b D_q}{\alpha^*} = C_2 \quad (7)$$

Here  $C_2$  depends on the initial mixture and  $\alpha^*$  is a quantity defined as

$$\alpha^* = \left( \frac{\lambda}{C_p} \right)_b \frac{1}{\rho} \quad (8)$$

where  $(\lambda/C_p)_b$  the quotient of thermal conductivity by heat capacity per unit mass, refers to the flame zone, but the density,  $\rho$ , refers to initial conditions.

14. Heimel, S.: NACA TN 4156 (1957).

15. Dugger, G. L., and Graab, D. D.: Fourth Symposium (International) on Combustion, P. 302, The Williams and Wilkins Co., Baltimore (1953).

16. Berlad and Potter: Combustion and Flame, vol. 1, no. 1, (1956) pp. 127-128.

17. Potter and Berlad: NACA TN 3882 (1956).

On combining Eqs. (6) and (7) so as to eliminate  $D_q$ , one obtains

$$\frac{U_b^2}{g_f} = \left(\frac{C_2}{C_1}\right) \alpha^* \quad (9)$$

The quantity  $\alpha^*$  may be related to the thermal diffusivity associated with the flame,  $\alpha_b$ , by the relation

$$\alpha^* = \alpha_b \left(\frac{\rho_b}{\rho}\right) \quad (10)$$

so that equation (9) becomes

$$\frac{U_b^2}{g_f} = \left(\frac{C_2}{C_1}\right) \alpha_b \left(\frac{\rho_b}{\rho}\right) \quad (11)$$

One may express the density ratio in terms of the ideal gas law,  $(\rho_b/\rho) = (M_b/M)(T/T_b)$ , where  $M$  is the molecular weight, and differentiate Eq. (11) logarithmically with respect to initial temperature for a single flame at constant pressure. If  $(C_2/C_1)$  is assumed constant<sup>17</sup> and the small change of  $M_b$  is neglected, there results

$$2 \left( \frac{\partial \ln U_b}{\partial \ln T} \right)_P = \left( \frac{\partial \ln g_f}{\partial \ln T} \right)_P + 1 + \left( \frac{\partial \ln \alpha_b}{\partial \ln T} \right)_P - \left( \frac{\partial \ln T_b}{\partial \ln T} \right)_P \quad (12)$$

Eq. (12) expresses the fact that  $U_b^2/g_f$  varies with initial temperature to a power slightly greater than one, the excess being given by  $\left[ \left( \frac{\partial \ln \alpha_b}{\partial \ln T} \right)_P - \left( \frac{\partial \ln T_b}{\partial \ln T} \right)_P \right]$ .

This quantity has been calculated by Eq. (12) with use of numerical values given in table I, and, as shown in that table, is found to be of the order of a few tenths. This result is consistent with the findings of Potter and Berlad, who examined the variation with initial temperature and flame temperature of a dimensionally similar group, the product  $U_b D_q^{17}$ .

Comparison of laminar and turbulent flashback. - At constant burner diameter, Eq. (3) may be expressed as

$$g_f(t) \propto \bar{U}_f(t)^{1.8} P^{0.8} T^{-(0.8+0.8w)} \quad (13)$$

where  $w$  is the exponential dependence of viscosity on gas temperature. Logarithmic differentiation at constant pressure gives

$$\left[ \frac{\partial \ln g_f(t)}{\partial \ln T} \right]_P = 1.8 \left[ \frac{\partial \ln \bar{U}_f(t)}{\partial \ln T} \right]_P - (0.8 + 0.8w) \quad (14)$$

The fact that critical boundary velocity gradients for both laminar and turbulent flashback show the same dependence on initial temperature implies that the temperature dependence of the mean stream velocity at flashback will be different for laminar and turbulent flames. Analogous differences exist between exponents on pressure and burner diameter at constant initial temperature<sup>9,10</sup>.

It has been noted that the critical boundary velocity gradient for flashback at constant pressure and initial temperature increases three-fold with change from laminar to turbulent conditions. This increase may be explained on the assumption that turbulent flashback takes place in that portion of the boundary layer where conditions are essentially laminar. Thus, if  $g_f$  is expressed as  $g_f = U_b/\delta$ , where  $\delta$  is the so-called penetration distance, the critical burning velocity  $U_b$  will remain constant with transition to turbulence, but the penetration distance will decrease by a factor of about 3.

Evidence has been obtained from measurements at room temperature that a turbulent flame at flashback is stabilized in a near-laminar portion of the boundary layer. This has been done by showing that the maximum stream velocity in the boundary layer for which conditions are essentially laminar,  $U_c$ , is greater at flashback than the normal laminar burning velocity at a given pressure<sup>9,10</sup>.  $U_{c,f}$  is given, approximately, by the expression

$$U_{c,f} = 0.75 \bar{U}_f Re_f^{-0.1} \quad (15)$$

obtained empirically from measurements of velocity profiles in tubes<sup>18</sup>. Similar verification that  $U_{c,f} > U_b$  at elevated initial temperatures may be obtained by comparing values of  $U_c$  for hydrogen-air flames near one atmosphere pressure with burning velocities obtained by Heimel<sup>14</sup>.

The decrease in penetration distance with turbulence can be made plausible by the following considerations. For a laminar flame, the coefficient governing heat transfer from the flame to the cold wall is nearly constant (its dependence on temperature being neglected) and the temperature profile nearly linear. For a flame stabilized in a field of turbulence which decays toward the wall, such as that which is found in the boundary layer for turbulent pipe flow, the coefficient for heat transfer is not constant, but increases inward from the wall toward the turbulent core. This causes a steepening of the temperature gradient very close to the wall and a flattening at larger distances. This is shown in Fig. 6. If the true penetration distance at flashback were rigidly defined in terms of the normal burning velocity and flame temperature, the flame could not take any advantage of the change in heat transfer to the wall. If, however, the true penetration distance were measured out to a point where the flame temperature was slightly less than normal, because of incipient cooling by the wall, the flame could take advantage of the steepening of the temperature gradient so as to penetrate much closer to the wall. It is presumed that the quantity of heat withdrawn from the main body of the flame to bring about the closer penetration would have no perceptible effect on the flame as a whole. The result would be, then, that the temperature gradient for the turbulent flame would be steeper than for a laminar flame and the penetration distance would be less, even though the rate of heat transfer from the flame as a whole would be greater. A relation between the change in penetration distance and the change in the actual dead space at the wall is shown in Fig. 6. The temperature  $T_e$  is slightly less than the normal flame temperature  $T_b$ , but probably considerably greater than  $T_q$ , the lowest temperature at which the flame can be maintained. It is possibly related to the temperature for which the curvature in the temperature profile is a maximum. In any event, we assume that it defines the penetration distance. Then the temperature  $T_q$  defines the dead space. It can be seen from the sketch that the two are related to the extent that a decrease in penetration distance is equivalent to a similar decrease in dead space.

18. Schlichting, H.: Boundary Layer Theory. McGraw-Hill Book Co., Inc., New York, (1955), p. 405.



## CONCLUSIONS

1. The dependence of  $g_f$  on initial temperature varies with the fuel-oxidant system. For reactive hydrocarbon flames the mass flow at flashback is nearly independent of initial temperature.

2. The variations of  $g_f$  and  $g_f(t)$  with initial temperature are the same for a single flame system. Therefore, the dependence on initial temperature of mean stream velocities at flashback is significantly different for laminar and turbulent flames.

TABLE I. - EFFECT OF INITIAL TEMPERATURE ON FLASHBACK OF BURNER FLAMES

System	Source of flashback data	$\left(\frac{\partial \ln g_f}{\partial \ln T}\right)_P$	$\left(\frac{\partial \ln U_b}{\partial \ln T}\right)_P$	Activation energy, kcal/mole	$\left(\frac{\partial \ln \alpha_b}{\partial \ln T}\right)_P - \left(\frac{\partial \ln T_b}{\partial \ln T}\right)_P$
CH <sub>4</sub> -air	Ref. 3	2.27	<sup>a</sup> 1.89 (ref. 4)	45	0.51
C <sub>2</sub> H <sub>4</sub> -air	Fig. 4	1.59	<sup>a</sup> 1.45 (ref. 4)	31	.31
C <sub>3</sub> H <sub>8</sub> -O <sub>2</sub> -N <sub>2</sub>	Fig. 3	1.02	1.06 (ref. 13)	--	.10
C <sub>2</sub> H <sub>4</sub> -O <sub>2</sub> -N <sub>2</sub>	Fig. 5	1.07	-----	--	----
H <sub>2</sub> -air	Fig. 2	1.52	1.44 (ref. 12)	19	.36

<sup>a</sup>Exponent obtained by disregarding data below room temperature.

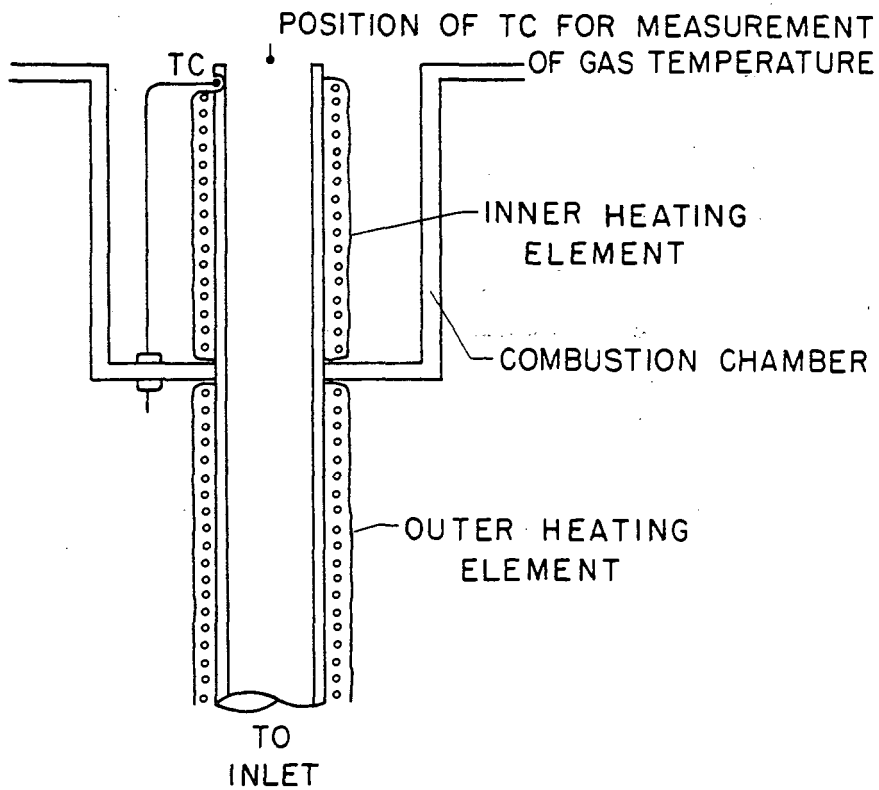
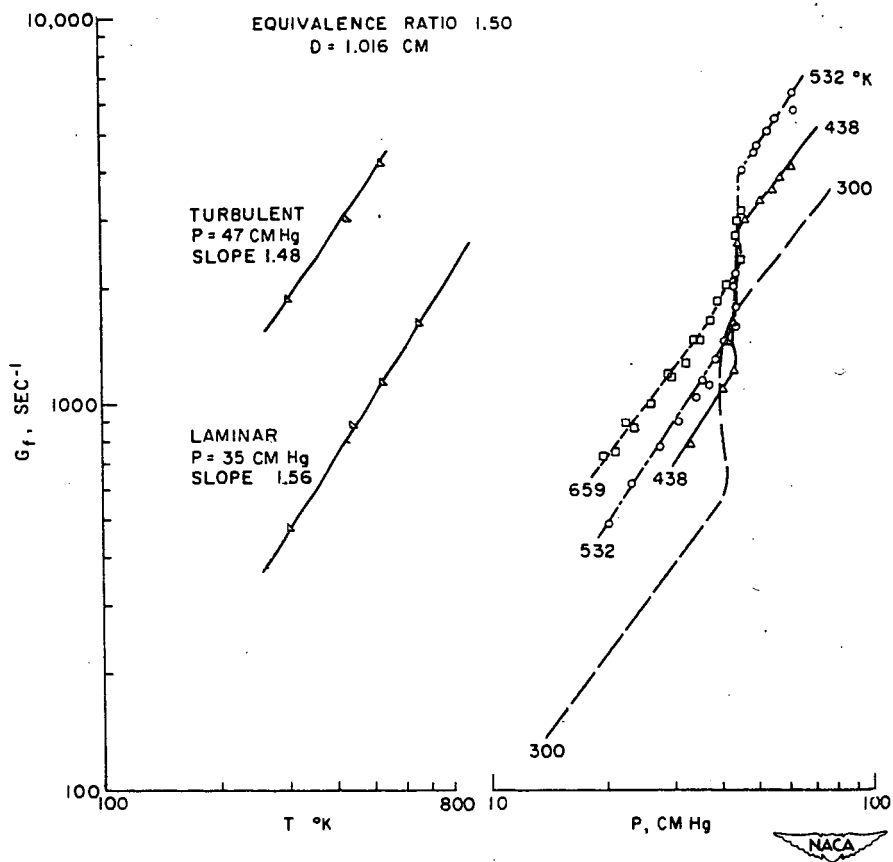


Fig. 1. - Burner head.

Fig. 2. - Flashback of  $\text{H}_2$ -air flames.

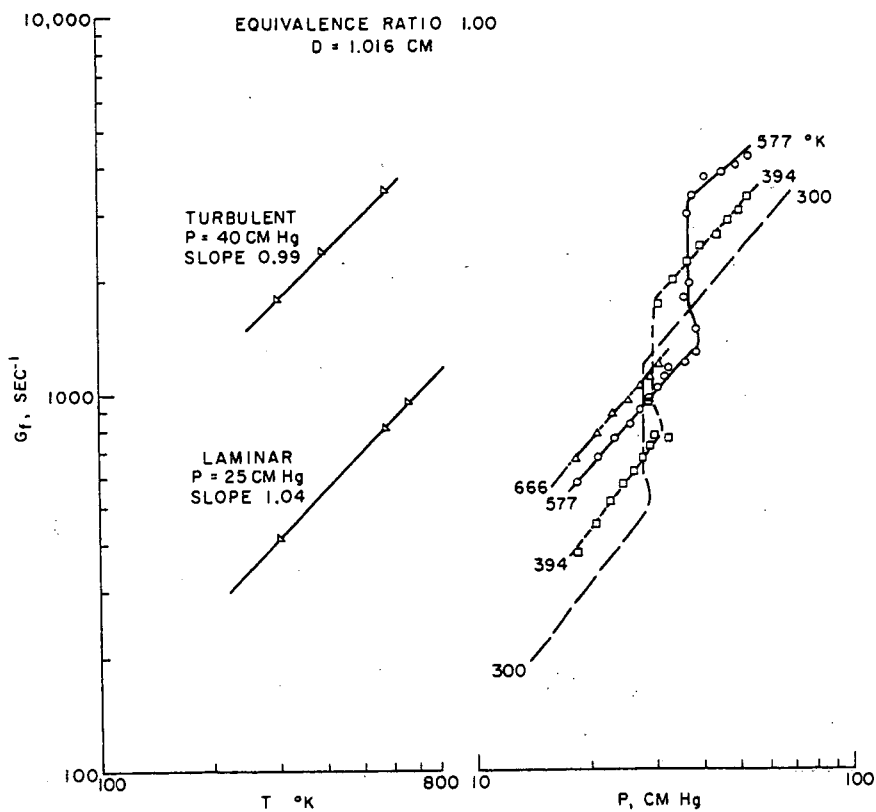


Fig. 3. - Flashback of  $C_3H_8-O_2-N_2$  flames.

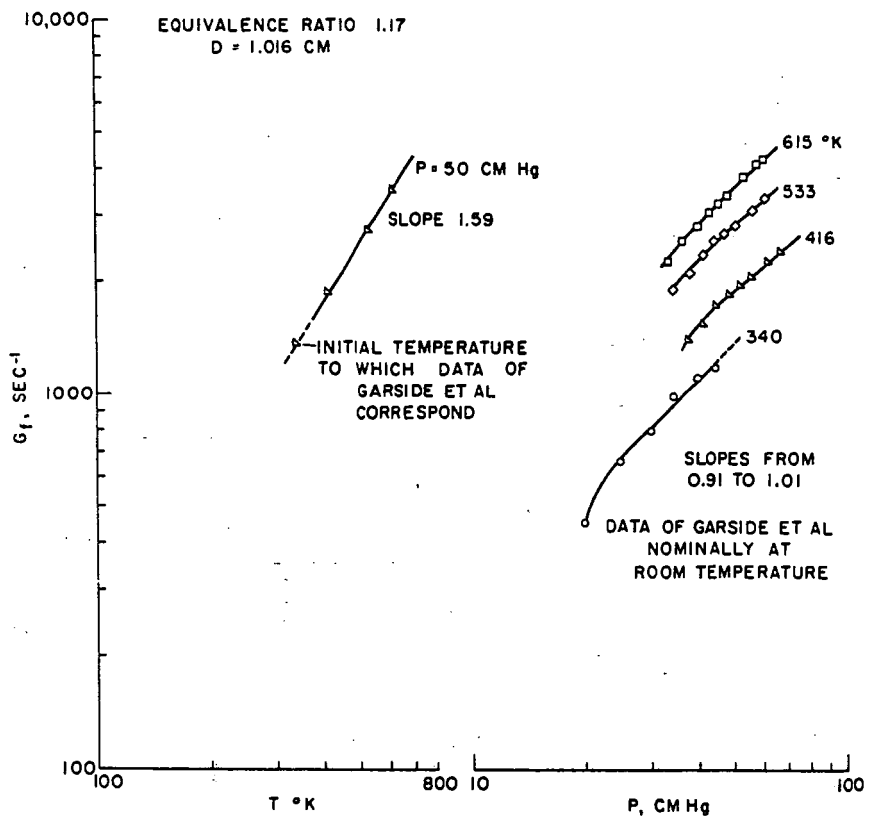


Fig. 4. - Flashback of laminar  $C_2H_4$ -air flames.

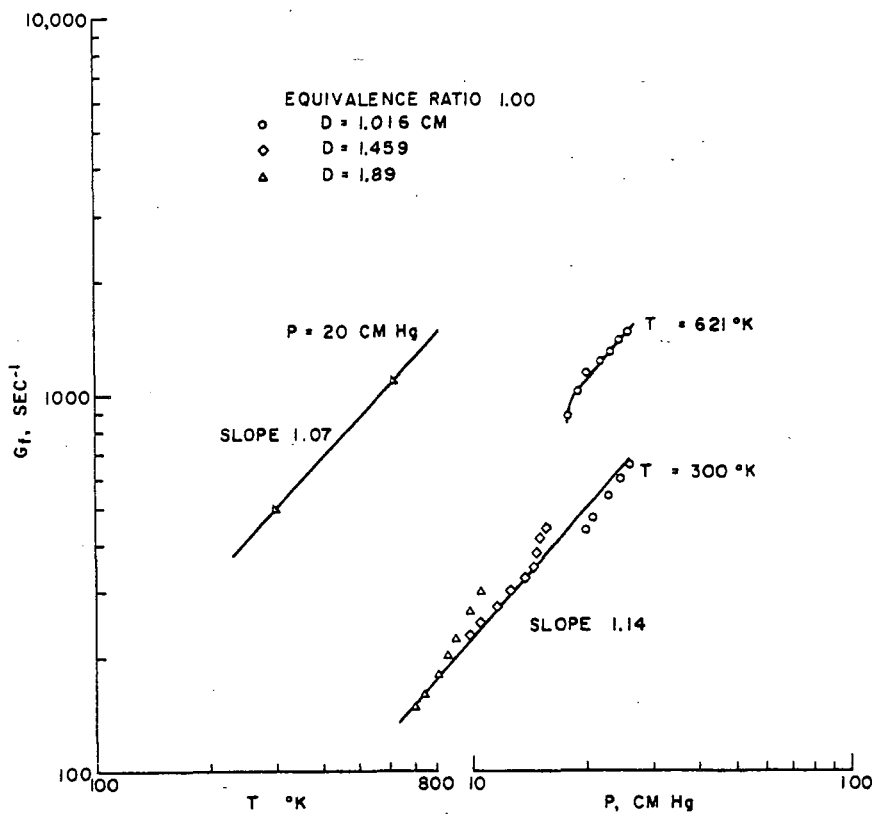


Fig. 5. - Flashback of laminar  $C_2H_4-O_2-N_2$  flames.

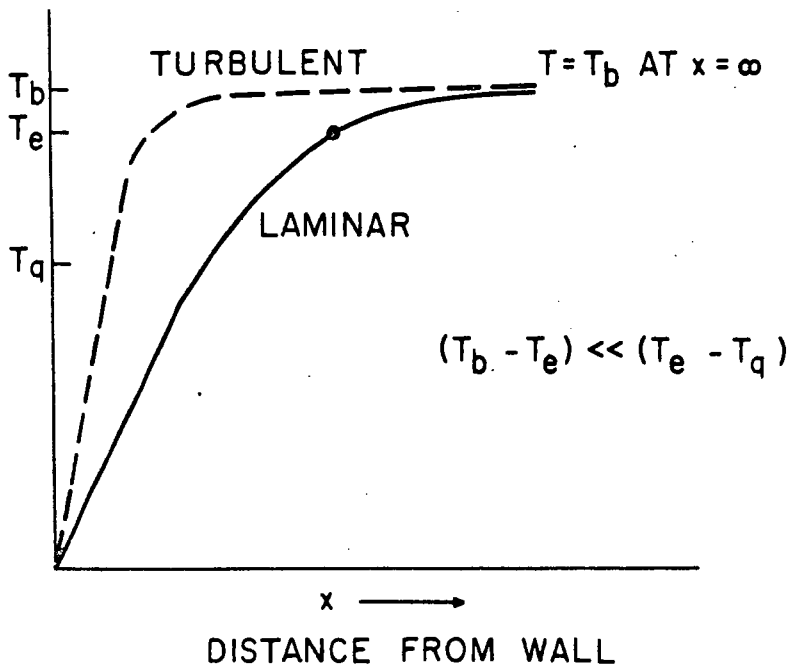


Fig. 6. - Hypothetical temperature distribution near wall for burner-flame (not to scale).